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Magneto-optics of superconductors with nanotailored pinning and with ferromagnetic layers

Gheorghe, G.D.

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Summary

This thesis unites a series of magneto-optical imaging studies aimed at providing a deeper understanding of some of the fundamental properties of conventional type-II superconductors, superconductor/magnet hybrids and molecular magnets. The first Chapter of the manuscript provides a basic introduction into the physics of these materials and casts each study into a broader context. Magneto-optical imaging, the main characterization technique used in this work, is described in detail in Chapter 2. By using the Faraday effect in thin indicator films (EuSe, Bi-doped YIG), the technique enables the direct visualization of magnetic field distributions and dynamic process in superconductors and magnetic materials. Our experimental set-up, a unique system that combines enhanced magnetic field sensitivity with the capabilities of a superconductor vector magnet, is also described in Chapter 2. By contrast to conventional magneto-optics systems, a polarization modulation scheme renders our set-up insensitive to uneven illumination and enables an accurate determination not only of the value, but also of the sign of magnetic fields at the surface of our samples.

Chapter 3 addresses the effect of misalignments of the magnetic field on current distributions in superconductors. Combining numerical simulations with experiment, our study reveals an angle-dependent, asymmetric flux penetration at the surface of a superconducting thick platelet exposed to an oblique magnetic field. The asymmetry is shown to become more pronounced with increasing tilt angle θ of the applied field H , relative to the plane of the platelet. Interestingly, the magnetic history of the sample also affects its current and magnetic flux distributions. Three different scenarios in which the sample is brought, along different paths, in a state characterized by the same parameters (H , θ), lead to markedly different magnetic flux distributions in the platelet.

Addressing two fundamental issues in superconductivity, the enhancement of the pinning properties, hence of the critical current, and vortex guidance and manipulation, Chapters 4-6 are dedicated to the investigation of type-II superconductors decorated with lithographically defined arrays of pinning centers.

Chapter 4 probes the pinning properties of thin films perforated by lat-

tices of antidots and blind holes. Our studies reveal a pronounced anisotropy in the flux penetration, with bundles of vortices advancing mainly along the lattice vectors of the patterned array. Although the artificial pinning due to both types of pinning centers is observed to dominate over intrinsic pinning, the latter becomes gradually more pronounced with decreasing temperatures and jeopardizes the guidance effect promoted by antidots and blind holes. Deep into the superconducting state, the magnetic flux penetration is dominated by vortex avalanches that obey a power-law distribution. Antidots display an extended avalanche regime, to magnetic fields larger by almost a factor of 4 as compared to blind holes, which indicates that they are more efficient pinning centers. Distinctively different magnetic flux distributions are observed in thin films decorated with identical lattices of antidots with different geometries, lower symmetry pinning sites leading to anisotropic distributions. This effect is purely of geometric origin, which we demonstrate by numerical simulations taking into consideration solely the electromagnetic properties of the systems.

The magnetic flux penetration in a superconductor decorated with a ratchet pinning potential is studied in Chapter 5. The properties of the ratchet, generated by an array of antidots of alternating size, are explored using two complementary techniques, transport measurements and magneto-optical imaging. Very close to T_c ($T = 7.13$ K), transport measurements reveal a clear reversal of the preferential direction of motion, with vortices advancing alternatively along the 'easy' and 'hard' directions of motion imposed by the underlying antidot array, as the external magnetic field is increased. A rectification effect is also observed by magneto-optical experiments. At high temperatures ($T = 6.7$ K), the ratchet potential leads to a pronounced anisotropy in the flux distribution, with enhanced flux penetration along the 'hard' direction of motion. With decreasing temperature this anisotropy gradually smears out and eventually reverses, such that deep into the superconducting state ($T = 2$ K) the flux penetration is strongest along the 'easy' direction. We show that this result can be understood within the framework of the thermomagnetic avalanche model.

By contrast to antidots or blind holes, magnetic dots provide not only the means to tune the critical current of a superconductor subsequent to decoration, but also to switch off thermomagnetic instabilities. We demonstrate these effects in Chapter 6 by magnetization and magneto-optical imaging experiments on superconducting films decorated with square lattices of Co/Pt dots with perpendicular anisotropy. Our experiments reveal that the pinning properties of the dots depend on the specific value of their magnetization and display a pronounced asymmetry as a function of the polarity of the applied magnetic field relative to their magnetic moment. The measured critical current densities are largest when the magnetic moment of the dots and the applied field have the same polarity and lowest when they

have opposite polarity, with a difference between extreme values of a factor of 2.5. At low temperatures ($T = 2\text{K}$), thermomagnetic instabilities set in only for high- j_c configurations. We show that these instabilities can be suppressed by tuning the magnetization of the dots. At high temperatures ($T = 5\text{ K}$ and above), a clear channelling of vortices along the lattice vectors of the dot array is observed. The morphology of these channels depends on the polarity of the applied magnetic field, which we explain as an effect of the interplay between the vortices introduced by the applied magnetic field and the vortices due to the stray field of the Co/Pt dots.

Chapter 7 introduces another hybrid system consisting of two superposed, superconducting (Nb) and magnetic (amorphous GdNi), thin rings. We observe strong electromagnetic interactions between the two layers. These lead to i) a rotation of the magnetization vector in the GdNi layer from an initial tangential to a final radial direction and ii) enhanced shielding of the Nb layer from the effect of external magnetic fields. The experimental observations are fully reproduced by numerical simulations that model the magnetic layer as a material with a large radial susceptibility.

Chapter 8 is, to our knowledge, the first magneto-optical imaging study of the prototypical Mn_{12} -Acetate molecular magnet. An inhomogeneous relaxation of the magnetic moment of the sample is observed below the blocking temperature T_B . The magnetization reversal proceeds systematically from the edge of the crystal corresponding to the highest local magnetic field, with a time lag between spin reversal at opposite edges of the crystal of the order of tens of milliseconds. We show that the observed magnetization dynamics is consistent with a magnetic avalanche with a wide propagation front and a long (compared to other values reported in literature) relaxation time.